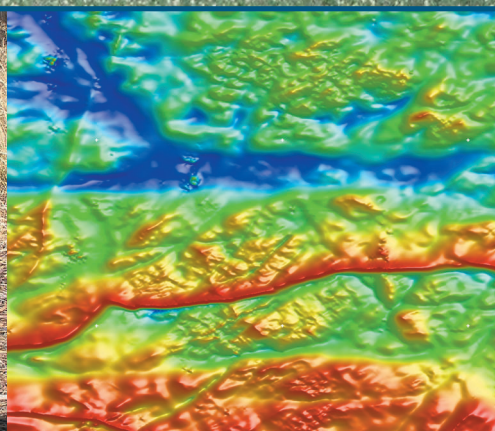
user guide

Brian Spies and Peter Woodgate

SALINITY MAPPING METHODS IN THE AUSTRALIAN CONTEXT

PREPARED FOR THE NATURAL RESOURCE MANAGEMENT MINISTERIAL COUNCIL



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Results of a review facilitated by the Academy of Science and the Academy of Technological Sciences and Engineering for the Programs Committee of the Natural Resource Management Ministerial Council through Land and Water Australia and the National Dryland Salinity Program

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FOREWORD

Our ability to effectively manage dryland salinity depends upon our understanding of its causes, location and behaviour in any landscape. Accurate mapping of the saline landscape and the hydrogeological pathways that control the movement of water and dissolved salt is critical if we are to understand its causes and develop measures for remediation. This user guide and its accompanying book describe the various methods that can be used in Australian environments to acquire and present information about dryland salinity. The user guide contains a summary description of each method and is designed to help the potential user determine how their mapping needs can be best met.

The user guide and accompanying book arose from a review of mapping methods that was commissioned by the Programs Committee of the Natural Resource Management Ministerial Council on the recommendation of its Science and Information Working Group. Following a public call for submissions, 36 organisations and individuals took the opportunity to make a contribution providing over 3000 pages of material. The project was overseen by a steering committee selected by the Operations Committee of the National Dryland Salinity Program.

The Australian Academy of Science and the Australian Academy of Technological Sciences and Engineering were invited by the Australian Government on behalf of the Programs Committee to review the outcome reports.

In order to fulfil their review function the joint academies undertook a number of activities.

- They first convened a workshop at the Academy of Science office in Canberra in September 2003, where 24 leading scientists were invited to critically examine the first working draft of the review and to offer advice on its further revision. The workshop was hosted by Dr Jim Peacock, President of the Australian Academy of Science and opened by the Secretary of the Department of Environment and Heritage of the Australian Government, Mr Roger Beale. It had as its guest Lord May of Oxford, President of the Royal Society. The day was chaired by Professor Brian Kennett of the Research School of Earth Sciences at the Australian National University.
- The academies then facilitated the involvement of leading scientists in the examination of specific issues as they arose in the re-drafting and we are grateful to the people who reviewed without prejudice relevant sections of the text of the draft reports as they were prepared.
- The academies then hosted a public forum at the Shine Dome, Canberra on 17 October 2003. The public forum was chaired by Dr Phil McFadden, Chief Scientist of Geoscience Australia. Over 70 participants spent the day reviewing the modified draft reports in a series of sessions that were guided by presentations from leading scientists in their field. The full transcript of the forum is available through the Academy of Science website at <www.science.org.au/conferences/salinity/>.

A panel of five scientists chosen by the joint academies undertook a final review of the reports. The panel members were Professor Kurt Lambeck (Chair), Dr Andy Green, Dr John Ive, Professor John Lovering and Dr Ian Rae. The panel was pleased with its positive interaction with the authors of the review reports.

The resulting user guide and book represent a thorough process of consultation, public examination and scientific review that will contribute to our ability to better map dryland salinity and its associated risks and hazards.

The Academy of Science and the Academy of Technological Sciences and Engineering are pleased to have facilitated the review and contributed to its successful completion through our consultative processes. We expect that the reports of the *Review of Salinity Mapping Methods in the Australian Context* will be an invaluable resource for a wide range of natural resource managers.

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ACKNOWLEDGMENTS

The authors would like to thank the 36 organisations and individuals who responded so willingly to the call for public submissions to the review, and to the many individuals involved in the review. The submissions and reviews comprised over 3000 pages of reports and papers in addition to the maps and CDs that are summarised in the appendices to the book. An extensive list of acknowledgments and references is contained in the book.

The authors are grateful for the assistance of the Project Steering Committee of Dr Sharon Davis (Chair), Dr Richard George—for his insight and extraordinary support in so many ways, and Dr Mirko Stauffacher; the Australian Academy of Science and the Australian Academy of Technological Sciences and Engineering; the Operations Committee of the National Dryland Salinity Program; and Mr Simon Veitch and Ms Annette Bleys.

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ABBREVIATIONS

AEM	airborne electromagnetics
ALS	airborne laser scanning
ALTM	Airborne Laser Terrain Mapper
API	air photo interpretation
CDI	conductivity-depth image
CRC LEME	Cooperative Research Centre for Landscape Environments and Mineral Exploration
DC	direct current
DEM	digital elevation models
dS	decisiemens
EC	electrical conductivity
EM	electromagnetics
GIS	geographic information system
GPR	ground penetrating radar
HEM	helicopter electromagnetics
km	kilometre
L	litre
LEI	layered-earth inversion
m	metre
mg	milligrams
MHz	megahertz
mS	millisiemens
µS	microsiemens
NDSP	National Dryland Salinity Program
NMR	nuclear magnetic resonance
OP	osmotic potential
ppm	parts per million
PRISM	Practical Guide of Salinity Models
S	siemens
SI	international standard
TDS	total dissolved solids
TEM	transient electromagnetics

(see also electromagnetic definitions, p. 33)

PREFACE

Salt is a *hazard* when it has the potential to be moved to where it can threaten assets such as agriculture, infrastructure, water resources and biodiversity. Salt stored in the ground may be mobilised by water and transported vertically and horizontally. Australia's growing problem of dryland salinity cannot be reliably assessed without a thorough three-dimensional understanding of the landscape and the hydrological processes that operate within it.

At least 26 satellite, airborne and ground mapping techniques are available for mapping and delineating soils, landforms, water flow and pathways through the subsurface.

- Some can be used to detect or infer the presence of salt at the Earth's surface or contained in the soil profile.
- Satellite and airborne remote sensing techniques can reveal existing surface salinity and can track changes over time.
- Airborne geophysical techniques, combined with ground and borehole control, are important tools in understanding salinity and hydrology at depth at a variety of scales.
- Only borehole sampling and electromagnetics (EM) techniques can detect and resolve salinity in the subsurface at depths in and below the root zone. EM techniques can also give complementary information on palaeochannels and structures which often control groundwater flow.

Salinity risk is a measure of the chance that the salt hazard will cause harm to an asset at some time in the future. Cost–benefit analyses in salinity management should take into consideration total cost and total benefit in context with the value of all assets.

The optimum strategy for mapping salinity hazard and risk depends on the scale (farm, community or catchment) and resources available to the user. Users need to make best use of existing information and then integrate a range of the available mapping methods so that they best address their specific problem. No single method has primacy, nor is there a 'magic bullet' for salinity mapping or prediction. Effective use of mapping methods requires expert knowledge or access to trained personnel.

This user guide describes and assesses methods for mapping dryland salinity, and addresses their applicability for assessing salinity hazard and risk. It is best read in conjunction with the accompanying book (available also on CD) which contains more detailed descriptions of ways to map, predict and monitor salinity and risk management. The book contains case studies that demonstrate applications of mapping techniques, as well as appendices with details of specific mapping techniques and a comprehensive list of references.

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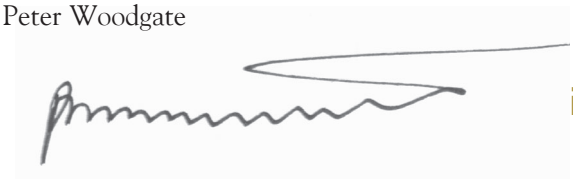

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SUMMARY

MAPPING HAZARD AND RISK OF DRYLAND SALINITY

1. Dryland salinity is the salinisation of land and water resources caused by the clearing of native vegetation for agriculture, particularly in dryland areas. This land-use change results in a rising of watertables and movement of salt to locations where it poses a problem for people or the environment. Assets at risk from dryland salinity include agriculture, water resources, built infrastructure and the environment.

2. In the context of dryland salinity, a **salinity hazard** is salt that can potentially cause harm to an asset. Salt is only a hazard if it has the potential to move into a location where it can threaten an asset, through mobilisation by surface and groundwater.

   A **salinity hazard map** defines the spatial location (both vertically and horizontally) and concentration of salt that can potentially be mobilised by water.

3. Water is the main agent that moves salt in the landscape. Mapping has important roles in delineating the location and extent of salt in the ground as well as identifying the hydrological pathways through which it is transported. In order to determine whether salinity has the potential to harm an asset, the suite of mapping systems must include those capable of collecting information about the factors that govern the hydrogeology of the area.

4. **Risk** is the likelihood that a hazard will cause harm to an asset at some defined place and time in the future. Risk is classically defined as an impact (usually an unwanted impact) multiplied by its likelihood of occurrence at some given time in the future. Assets include agriculture, water resources, built infrastructure and environmental attributes such as biodiversity. **Salinity risk maps** should identify the actual class of asset under threat, the timing of the impact of that threat, the level of anticipated impact should it occur, and the geographic location of both the risk and the asset.

5. Preliminary analyses for hazard assessment should first use existing data sets to develop an overview of the landscape and to identify priority areas for detailed mapping. Such an approach can also be used over large areas (multiple catchments or State/Territory level).

6. Salinity risk management should endeavour to prioritise areas, information needs and mapping methods for appropriate levels of detailed investigation. A sieving approach, moving from general overview to specific detail based on progressive investigation and analysis, can identify priority areas for appropriate types of mapping.

7. An integrated geoscience or systems methodology, employing three-dimensional mapping of landscape, salinity and groundwater elements, will increasingly provide valuable insight into salinity processes and salt store distribution. It builds upon the groundwater flow systems approach which to date has mainly been applied at regional scale and in most cases is limited to two-dimensional models. Both techniques can be applied at any scale where three-dimensional information is available.

8. All mapping techniques should be 'ground-truthed' and calibrated through field inspection prior to the finalisation of the mapping program , and in many cases before a mapping program is commenced. Field measurements (including soil sample measurements and borehole logging) should be an integral part of any mapping campaign and take into account the three-dimensional nature of the earth and statistical spatial variations within the subsurface.

9. As a general rule it is advisable to plan to undertake independent assessments of the veracity of all major mapping programs at the conclusion of mapping. Such validations provide sound justification for the subsequent decision-making phase by confirming the accuracy and uncertainty associated with the mapping products. They are also a valuable learning tool.

10. Most mapping systems require a high level of expertise for their sound use. Prior experience and a proven track record in understanding the acquisition, processing and interpretation phases is highly desirable. Users are advised to seek specialist advice before committing resources to mapping programs.

11. A balance needs to be struck between the need for data at fine resolution at paddock scale and the broader benefits that are possible when data are combined to produce a bigger picture at catchment, State/Territory and national levels. Some of the systems reviewed (e.g. radiometrics and electromagnetics) can be used at both an overview and detailed scale.

12. The technologies that are suitable for mapping dryland salinity risk and hazard are evolving rapidly. Australia is particularly fortunate to have an excellent science community that supports the development and deployment of new mapping methods as they continue to evolve.

13. Substantial investments have been made, and will continue to be made, in the collection of data for salinity management. These data require systematic coordination, storage and management in order to maximise their value. Such coordination can ensure the appropriate application of standards as well as help to identify properly credentialed specialists.

CONCLUSIONS ON SPECIFIC MAPPING SYSTEMS

14. The 26 mapping methods covered in this review can be used in some way to map salinity hazard and/or risk. The optimal choice of methods depends on the scale of mapping, the vertical and horizontal resolution required, availability of finances, pre-existing knowledge and complementary data sets.

15. Two techniques (laboratory measurements and measurements of soil paste extracts) are useful as analytical point measurement techniques of salt content.

16. Eleven techniques (visual inspection, satellite [e.g. Landsat and SPOT] and airborne remote sensing, air photos and digital elevation models [DEM]) can be used for surface mapping in the 0 to 10 cm depth range. Some of these methods give direct information about salt at the surface, while others give indirect information on salinity in the root zone through interpretation of vegetation stress. Others, such as radiometrics, are useful for soil mapping. Visual inspection, air photo and DEM interpretation, multispectral satellite imagery, and ground electromagnetics (EM) are well developed operationally.

17. Ground electromagnetic conductivity mapping and ground-penetrating radar can be used to probe to several metres into the Earth to give information on salt load and/or moisture content. Of these, electromagnetic conductivity mapping using instruments such as the EM38 is the most cost-efficient technique and has wide utility at farm, community and subcatchment scale.

18. Eight methods can be used to probe deeper than 2 m into the subsurface and map at high resolution. These include deep EM (such as EM31) and electrical probing methods, borehole conductivity logging and stream sampling, all of which give information on salt load. Several methods (ground magnetics, seismic) can be used to help delineate palaeochannels and barriers to subsurface flow. Two methods (nuclear magnetic resonance and seismo-electric) show promise for groundwater detection but are expensive and only used in research mode at present.

19. Airborne electromagnetics and airborne magnetic methods can be used for deep probing (greater than 2 to 5 m) on a subcatchment to regional scale. Only one system, airborne electromagnetics (AEM), offers a proven approach to broad area mapping of salt store below the root zone using a range of airborne platforms. Although relatively expensive, AEM has been used in dozens of studies over the past decade. It has some limitations at shallow depths (less than 5 m below surface) that are now being addressed through applied research. AEM also has limitations in areas where there are complex variations in vertical patterns of salt store and geology. Careful attention should be paid to all stages of survey design, acquisition, processing interpretation and ground calibration to maximise the utility of AEM.

20. Many mapping methods are used in combination, and some are acquired simultaneously. The skill base in each technique is highly specialised, and there are few users who are expert at more than two or three methods.

21. Some vendors' claims that their techniques directly detect salinity are unsubstantiated (e.g. some radiometric and remote sensing proponents claiming direct detection of salinity). It is good practice for potential users to seek independent advice on claims made by vendors.

1. INTRODUCTION

Salinity mapping methods in the Australian context (the user guide and book) provides up-to-date information about ways to map dryland salinity and strategies for making investment decisions for salinity management. The user guide provides a broad overview that is directed towards a general readership. The companion book contains an expanded description of techniques for salinity mapping, prediction and monitoring, as well as strategies for risk management. The book also contains references to published literature, case studies and extensive appendices with details of specific mapping techniques.

How can the user guide help?

The user guide will let you know more about how to map the current extent of dryland salinity hazards or predict the risk of dryland salinity. It examines the information needs of:

- the farmer at paddock level;
- the community at subcatchment level;
- regional catchment planning authorities; and
- State, Territory and national authorities.

The user guide explains the difference between salinity hazard and risk, and briefly describes the origins of dryland salinity. It provides detailed information about methods to map dryland salinity and the geological and hydrological processes that control its development. The guide also covers investment decisions and the cost, skill level, applicability and limitations of each method.

The guide will help identify optimal approaches to obtaining information about salinity problems and help people make better decisions about management options.

It is useful for informed practitioners of mapping techniques as well as experienced land managers and/or their advisors. Both these groups should be involved in any decision to proceed with new mapping and in any subsequent decisions affecting land management. Such involvement will help ensure a high standard of mapping and the acquisition of the most reliable information.

Photo: Pauline English. © CSIRO 2005. Reproduced with permission.

If you want to know more ...

More detailed information on all the salinity mapping methods detailed in the user guide can be found in the book (available both in paper form and on CD). The book also contains a bibliography and case studies for further reading.

Further information on salinity mapping and risk assessment can also be gained by contacting the National Dryland Salinity Program (NDSP) <www.ndsp.gov.au/>. The NDSP published a summary of its ten years of knowledge in its Managing Dryland Salinity in Australia suite of publications in July 2004. Other information on dryland salinity is also available from the National Land and Water Resources Audit website <www.nlwra.gov.au>.

Additional specialist expertise and knowledge of mapping systems can be obtained from government and industry sources, in particular:

- Cooperative Research Centre for Landscape Environments and Mineral Exploration (CRC LEME) <www.crcleme.org.au/>;
- Geoscience Australia <www.ga.gov.au/>; and
- other relevant State/Territory and Australian Government natural resource management agencies.

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2. USER NEEDS

CLASSES OF USERS

Many individuals and organisations have an interest in salinity and a need to understand the presence and extent of current salinity. They may need to assess potential risks and management options arising from changes in salinity. Users range from individual farmers, to communities, catchment groups and regional authorities. Questions related to salinity depend to a large extent on the needs and budget of the user. Answers to these questions help users to make better management decisions.

Farm scale

Farmers have immediate, personal and business-related interests in salinity and while some may know about salinity indicators, others may not. Farmers usually focus on obtaining useful information at the paddock scale.

Key questions the farmer is likely to ask are:

- *Are there any indicators of salinity on my land?*
- *If so, how much more salinity am I likely to get, and when?*
- *Are my land management activities contributing to the problem?*
- *Is this salinity currently damaging any of my assets?*
- *If not, are there risks to any of my assets in the future?*
- *What can I do to stop it?*

Farmers often consider the cause of the salinity to be of secondary importance, except in the context of how the salinity can be best managed and the desire to be a good community or catchment citizen by minimising impacts to others.

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Local community

A local community may consist of between 10 and 20 neighbouring farms that may have similar soils and hydrological flow system, located within a subcatchment. Their questions are likely to be similar to those asked at the farm scale, but with a greater community orientation.

- *How much salinity are we likely to get, and when?*
- *How serious is it now and how serious will it be in the future?*
- *What can we do to stop it?*
- *Is there anything we need our neighbours to do to stop it?*
- *Is there anything we can do to prevent us making it worse for our neighbours?*

Depending on their location within the landscape, some individuals in the community will find that their salinity problem will become worse, while others find that the problem will lessen as a result of the remedial action taken by themselves and/or their neighbours. This can raise the shared issues of equity and cost.

Community participation in salinity mapping.

Photo: Pauline English. © CSIRO 2005. Reproduced with permission.

Catchment management groups

The operating area for regional-level planning for dryland salinity is the catchment level, where one or more catchment management groups have overall responsibility for developing an integrated management plan. The Australian Government is working with State and Territory governments, and catchment management groups to achieve effective action to manage salinity. In such regions typical questions are:

- *What is the overall level of the problem in the region?*
- *How do managers get that right mix of actions that tackle prevention, recovery, containment and adaptation?*
- *Where are the best locations to put in salinity management options (e.g. drainage, revegetation works, salt interception schemes) that will deliver the salinity target (e.g. mg/L of salt being exported to the river, or lowered watertable) in the most cost-effective fashion?*
- *What information is needed to make sound investment decisions at this level?*

Investment decisions might be expressed in terms of an investment framework of where is it best to invest funds to maximise benefit (e.g. into mapping, modelling, new research and development or into on-ground interception works).

Other dryland salinity management scales such as the expanse of the Murray–Darling Basin also exist.

State/Territory and national levels

State/Territory and Australian governments have responsibilities and roles in managing dryland salinity. Questions at these levels include:

- *How much salinity is present, what is the distribution (both in land and rivers) and what are the trends (e.g. mg/L of salt, hectares affected or depth to watertable)?*
- *What is the impact likely to be on various classes of assets, and what are the priorities for management?*
- *What are the management options (e.g. where to locate interception schemes to achieve a target of a certain concentration measured in mg/L at Morgan?)*
- *Which environmental asset is of greatest priority, is at greatest risk and can be viably managed?*
- *What will the impact be on other areas if funds are insufficient for management? What resource sharing is required for investments outside the asset to manage the long-term ecological function and use of the asset?*
- *What are the overall effects of management options on whole communities through time?*
- *What are the priorities for management of other forms of land degradation and the opportunities for synergies for actions to tackle them together?*
- *In which initiatives should Australian governments invest to generate the best outcomes in relation to sustainability and profitability?*

Saline discharge in the Goondoola Basin, south-west QLD.

Photo: Kate Wilkinson.

Overall

At all scales the user needs to consider whether the existing information or knowledge base is adequate to address the hazard, risk and management responses. Additional questions a user might ask are:

- *Am I sure of the cause of the salinity?*
- *Will additional knowledge increase my capacity to more effectively manage the risk?*
- *Is new mapping, modelling or research and development required (and how much does it add to what do I have access to now)?*
- *Can I conduct this mapping myself or is other expertise needed?*
- *What are the relative costs and benefits?*
- *Who will bear the cost and who will gain the benefit?*

These questions are more complex for statutory land managers since they need to:

- understand salinity hazard and risk at all scales;
- balance competing interest groups; and
- use available funds to generate maximum return for public investment.

The key stakeholder is identified as the one who has the capacity and responsibility to study and manage the problem.

MAPPING SCALE

Scale is the ratio of the dimensions of objectives in real life as represented on maps. They are mainly expressed as the following simple ratios.

1:10 000
1 mm on the map is equivalent to 10 m on the ground, and 1 square mm is equivalent to 0.001 ha. This is a useful scale for representing *paddock level* information.

1:50 000
1 mm on the map is equivalent to 50 m on the ground, and 1 square mm is equivalent to 0.25 ha. This is a useful scale for representing *subcatchment level* information.

1:100 000
1 mm on the map is equivalent to 100 m on the ground, and 1 square mm is equivalent to 1 ha. This is a useful scale for representing *subcatchment and catchment level* information.

1:250 000
1 mm on the map is equivalent to 250 m on the ground, and 1 square mm is equivalent to 6.25 ha. This is a useful scale for *regional* representations.

1:500 000
1 mm on the map is equivalent to 500 m on the ground, and 1 square mm is equivalent to 25 ha. This is a useful scale for *regional and State/Territory* representations.

1:1 000 000
1 mm on the map is equivalent to 1 km on the ground, and 1 square mm is equivalent to 100 ha. This is a useful scale for *State* representations. Forty-one 1:1 000 000 map sheets are required to cover Australia.

The larger the scale the closer one gets to the real life object. Thus 1:10 000 is considered to be large scale in relation to 1:1 000 000 which is considered to be small scale. Expressions of local, regional and national scales are also commonly used.

INVESTMENT DECISIONS (COSTS AND BENEFITS OF MAPPING AND MANAGING SALINITY)

The relative costs and benefits associated with obtaining new information is a central consideration for land managers wanting to know about dryland salinity on their land. A simple five-step plan addresses this issue.

Five-step plan for assessing the need for new information

Steps 1 to 4 will produce a prioritised list of areas for which new mapping is likely to yield useful information, the costs of doing so, and the value of the assets to be mapped or affected by salinity. Step 5 considers the likely cost of possible management actions following acquisition of new information and the likely benefit of undertaking these management actions.

Step 1: Determine the value of the assets potentially at risk

A number of categories of assets are at risk from dryland salinity including agricultural productivity, infrastructure (e.g. roads, townships), water resources and biodiversity. Maps showing the location and value of these assets can help target areas and concentrate the effort required to collect new information and undertake any land-use actions.

Step 2: Assess the current level of knowledge about dryland salinity in the area of interest

Areas where we currently have a poor level of knowledge of the natural environment may be more likely to benefit from new information. Existing information should always be compiled and assessed to gain maximum understanding of landscape and hydrological processes before additional mapping is undertaken. State/Territory governments often have geoscience spatial information freely available that may be of assistance in understanding dryland salinity.

Step 3: Consider whether the mapping techniques you are proposing to use are suitable for the specific environment

Not all mapping techniques are applicable in all environments—some may be better suited to specific problems or be more cost-effective. Sequential or combined use of two or more methods may provide the most cost-effective and timely information.

Step 4: Identify areas where no useful remedial action is possible

In saline areas where no remedial action is likely to be available or new data is unlikely to improve or support remedial action, the acquisition of new information may have limited merit unless it assists in the understanding of salinity changes in a regional sense or serves to assure stakeholders that the optimum course of action is already being followed.

Step 5: Apply the benefits of this approach

Evaluate the benefits and costs of the mapping and interpretation proposal. The budget should include costs of pre-survey design, data acquisition, ground-truthing and calibration with borehole control, and interpretation.

3. SALINITY

WHAT IS DRYLAND SALINITY?

Soil salinity refers to the presence of salt in solution (plus readily dissolvable salts) in the soil. Soils naturally contain a broad range of solutes, the most common being sodium chloride, but lesser amounts of other salts such as potassium and sulphates are also common. Soil salinity is either primary (naturally occurring salinity) or secondary (due to land-use impacts by people). Secondary salinity can be divided further into dryland and irrigation salinity.

These categories relate to its cause rather than its chemical or physical character and the same techniques are used to measure and map salinity irrespective of its origin (natural, dryland or irrigation). The main difference between dryland and irrigation salinity is in the management options available to address the salinity risk.

CAUSES OF DRYLAND SALINITY

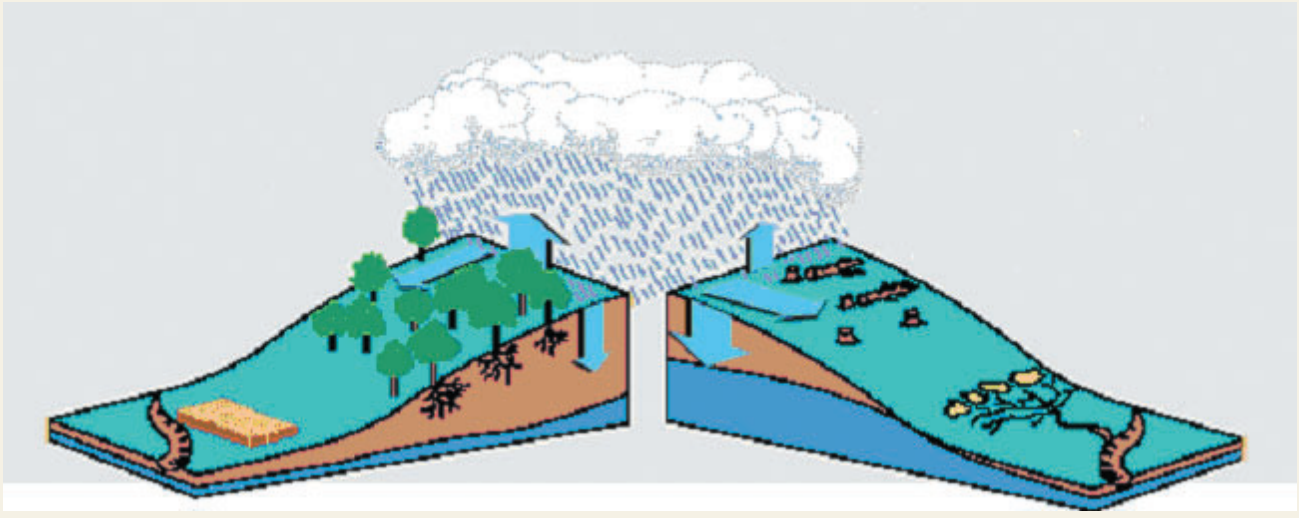
Dryland salinity is caused by rising watertables and the concentration of salt in locations where it poses a problem for people or the environment. The watertable rises when water enters the ground at a greater rate than it can drain away horizontally or vertically. Salt is either concentrated at the surface by evaporation or discharged into adjacent land, drainage systems or surface water bodies.

Another type of salinity known as 'dry saline land' is not hydrologically connected to a saline watertable, and often occurs in upland, winter-rainfall zones such as semi-arid regions of New South Wales, Western Australia and South Australia. Dry saline land can occur as high levels of salinity at the surface, or deeper in the root zone or subsoil (0.3 to 1.0 m) with salinity trends increasing from the surface into the subsoil. Dry saline land can exist as either primary or secondary salinity.

SALINITY IN THE MURRAY–DARLING BASIN

Dryland salinity in the Murray–Darling Basin has arisen from changes in the water balance following removal of native vegetation and introduction of European agricultural practices, most significantly the adoption of shallow-rooted annual crops and pastures. Native vegetation has a great capacity to optimise water use. Its extensive root systems draw water from deep within soils during dry times, serving to increase the soil water deficit and provide 'room' for the next season's rainfall (Figure 1). This reduces the tendency for waterlogging.

Figure 1. The salinisation process in a dryland catchment. The native deep-rooted vegetation keeps watertables low; when the land is cleared, the watertable rises and mobilises salt. Drawing: Salt Action NSW.



SALINITY HAZARD, RISK AND IMPACT

*Do I have a **salinity hazard**? Do I have salt in the landscape somewhere on or under the land that may pose a risk to assets, and if so can the risk be managed?*

Salt is a natural part of the Australian landscape. It becomes a **hazard** when it has the potential to move to a location where it can threaten an asset. Salt moves in the landscape when it is dissolved and transported by water. A **dryland salinity hazard** is the combination of salt with the potential for movement by surface water and groundwater.

Mapping salinity hazard involves describing the extent, depth and concentration of salt as well as hydrological features that may affect water movement in the landscape. Mapping systems either directly detect salt in the landscape (e.g. chemical analysis of soil at the surface or in boreholes) or indirectly infer its presence through its effect on vegetation or by observing changes to electromagnetic conductivity signals. Mapping techniques can also be used to give insights on pathways for groundwater movement.

*Is the land area that I manage and the assets that I value **at risk** of being adversely affected by dryland salinity at some time in the future?*

The question of **risk** implies more serious consequences than hazard. **Risk assessment** is far more complicated than salt hazard mapping because it requires an understanding of the factors that govern the movement of salt to locations where assets may be damaged. Risk implies a prediction about the severity of the damage and when it will occur. Evaluation of risk involves estimating both the **likelihood** of salt affecting an asset within a certain time frame and the **impact** (or degree of severity) on the assets should the event occur. Assets at risk are often located at great distances from the source of the land use that may have caused the salinity.

The combination of salt and water is critical. Areas with low concentration of salt, when combined with high flow and high evaporation rates can result in a higher hazard and risk than areas with higher salt load but lower flow and evaporation rates.

Photo: Pauline English. © CSIRO 2005. Reproduced with permission.

Many factors affect the rate, location and destination of surface water and groundwater:

- *Climate* is the long-term cycle of droughts and rains, evaporation and precipitation. It moderates the water cycle through time.
- *Weather* is the local affect of rain and sunshine and determines the water cycle over shorter periods.
- *Land use and land management*—tree clearing and replacement, agricultural practices, borehole water use and the installation of drains—are the most powerful human activities affecting the water cycle and hence dryland salinity.
- *Terrain* includes the steepness of the land, location of streams and rivers, and break of slope. The combination of terrain and gravity drives water through the landscape.
- Different *soils* have different permeability to water flow and different susceptibilities to the development of salinity.
- *Regolith* is the unconsolidated material between the surface and bedrock. It varies in its ability to allow water to permeate and move elsewhere and may contain preferential pathways for water movement.
- *Structural features in the bedrock* can act as barriers or carriers to the passage of water.
- *Ancestral or prior river and stream systems* are known as palaeochannels. These buried, ancient stream or river systems can preferentially promote the passage of groundwater.
- *Geological faults and dykes* may also act either as underground channels that encourage the movement of water or act as barriers.
- Plant roots take up water from the ground. Different *vegetation types* of varying ages and densities use different amounts of water. They also have differing abilities to tolerate salt in the soil.
- The salt content of *groundwater* and its rate of movement varies with location, depth and soil type.

HAZARD AND RISK

Hazard refers to anything that can potentially cause harm to an asset. Salt becomes a hazard when it has the potential to move into a position where it has the ability to threaten an asset. Water is the main agent that moves salt in the landscape. A dryland salinity hazard results from the combination of salt and the potential for movement by surface or groundwater.

Risk is the chance that a hazard will cause harm to an asset at some defined time in the future. Risk is classically defined as an adverse impact multiplied by its likelihood of occurrence at some given time in the future. In effect, it is a way of weighting possible unwanted events by their likelihood. So a highly unlikely but serious impact may be regarded as presenting the same risk as a likely but minor impact.

In order to predict salinity risks the behaviour of each of these factors needs to be understood and described. Their combined interpretation can then be used to prepare maps of salinity risk that show the extent, severity and timing of the threat of dryland salinity in relation to assets being considered. A 'risk map' has higher inherent value (and is more likely to be acted upon) if it is targeted at the particular asset for which management decisions need to be made. Modelling techniques are normally used to forecast risk (see p. 43).

Hazard maps and risk assessments can be prepared for immediate use by land managers. Confidence in the assessment will be directly influenced by knowledge of the scale of the processes driving the hazard or risk, and this knowledge will be determined largely by the scale, quality and quantity of the data available. People making these decisions need to understand the level of confidence that is associated with their decisions.

Electromagnetic conductivity profiling using a 4-wheel bike.

Photo: Courtesy Geoforce

MEASURING SOIL SALINITY

Ideally, we need to know the concentrations of individual salts in the soil under the entire range of field water and land-use conditions, particularly when soil sodicity (a measure of the sodium content that affects soil structure) or toxicity of specific components are to be assessed. This is **direct** measurement of soil salinity. Very few mapping techniques measure salt directly. Direct measurements include visual inspection, analysis of total soluble salts and laboratory analysis of soil samples. Salinity maps can be constructed based on compilation of individual point measurements.

However, the collection of direct information may be very costly and these measurements are usually restricted to laboratory studies of small samples from specific points locations at a specific time. In practice and over large areas **indirect** mapping techniques are used to infer the likely presence of salt. Indirect techniques include those that measure the declining health of salt-affected vegetation and methods that respond to the electrical conductivity of salt loads beneath the surface. They include:

- aerial photos—measuring optical reflectance at visible wavelengths;
- satellite imaging—that can 'see' changes in the health of vegetation; and
- airborne and ground electromagnetics—measuring electrical conductivity, which is closely related to salt content.

Some of the same mapping techniques can also be applied to mapping groundwater, variations in moisture content. Radiometrics (gamma-ray spectrometry) is widely used for identification of soil type.

Rapid indirect techniques based on electrical conductivity measurements are now the preferred method for inferring salinity in the root zone.

DIRECT VERSUS INDIRECT MEASUREMENT

Direct methods of salinity measurements are based on laboratory analyses of soil samples (with care taken to preserve water content) and identify specific ion concentrations.

Indirect methods infer the level of salinity and several techniques are used. The most common indirect method, and that most closely related to salinity is electromagnetic conductivity (see box p. 16 for further detail). Electrical conductivity (EC) depends on the type of solute, clay content and moisture levels. EC meters operate at a variety of scales, from portable conductivity meters to deeper-probing surface-based and airborne methods.

Other indirect techniques are, in effect, extensions of visual inspection, where large areas are investigated from aircraft or satellites. These methods based on measurement of electromagnetic or other radiation at various wavelengths, and include photographs, multispectral and hyperspectral scanning and measurement of gamma radiation.

A SYSTEMATIC APPROACH TO RISK MANAGEMENT

Mapping projects should always be designed to achieve the intended outcomes in the most cost-effective manner We need to:

- decide the types of risk to be considered (e.g. arising from increasing salinity);
- identify the assets to be protected (e.g. farms, forests, water supplies, biodiversity, residential areas) and whether they are diffuse targets (e.g. forests) or single points (e.g. specific buildings);
- identify the decision makers and those people who may be affected either inside or outside the area covered by the investigation (e.g. farmers, local residents, regional authorities);
- decide the time frame of interest (e.g. now or in 10, 20 or 50 years); and
- remember that assets at risk from dryland salinity are often located some distance from the human activity that causes dryland salinity and that non-agricultural interests are also at risk.

A plan that identifies options and actions to intercept the water that moves the salt may also be required.

A risk management strategy also requires ongoing monitoring and review to determine any significant change from predictions and any notable failure or success of the risk-reduction actions taken. However, the impact of remediation actions may not be visible for many years.

Dryland salinity in south-western Victoria.

Photo: Baden Williams

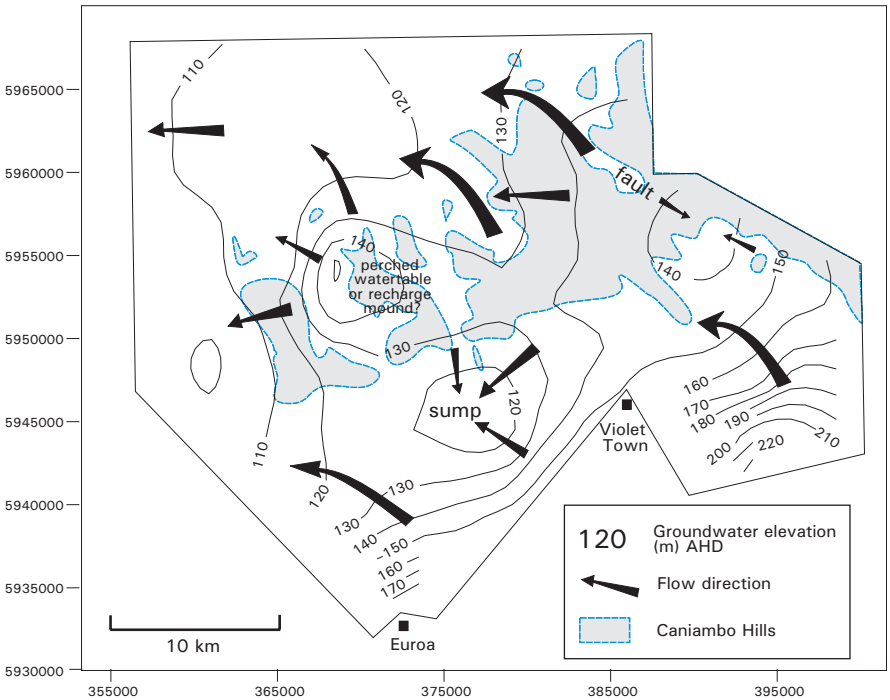
THE ROLE OF MODELLING

Modelling techniques can be applied to predict salinity movement, for example, groundwater flow system models build on a suite of fourteen factors including landform, aquifer transmissivity, temporal and spatial distribution of recharge, and responsiveness to options in land management. Other modelling systems produce a two-dimensional picture of the rate of flow of groundwater down through the catchment through specific locations.

Modelling requires knowledge of the hydraulic gradients, surface drainage features and permeability of the regolith and soil and other factors.

Combining modelling systems from different scales enables planners to better predict the likely location of dryland salinity. These predictive models are only as good as the data that they use, the quality of the understanding of the complex interactions of the factors of the landscape and the strength of the decision rules that are applied to drive the model.

Groundwater flow direction inferred from watertable levels (courtesy Pauline English, CSIRO).



Electrical conductivity is an easily measured and practical index of the total concentration of ionised solutes in the sample, and is the most common technique for inferring salinity in soils. Many techniques for measuring the electrical conductivity of soils have been developed. The most common techniques are EC extracts of paste-water samples and the measurement of bulk electrical conductivity of soil (EC_a) with portable terrain conductivity meters. Borehole and airborne sensors are also used, depending on the level of detail (scale) required. Measurements of electrical conductivity include those made on:

- soil samples—extracts of a saturated soil-paste sample (EC_e), or solutions of that paste;
- water samples—extracted from soil (EC_w);
- larger volumes of soil, either from the ground or air (EC_a).

Units

A variety of units are used for measures of salinity and EC. The international standard (SI) unit for conductivity is siemens per metre (S/m), and EM instruments are commonly calibrated to read milli-siemens per metre (mS/m). EC_e units are commonly quoted in dS/m (decisiemens per metre) or μS/cm (microsiemens per metre). This guide uses mS/m (100 mS/m = 1 dS/m = 1000 μS/cm).

Other units include parts per thousand, parts per million (ppm), milligrams per litre (mg/L), osmotic potential (OP) and percentage total soluble salts in a 1:5 mix. Various approximate factors exist for relating salinity measures but are based on assumptions on salt and soil type. As a rough guide, water with 15 000 mg/L TDS (total dissolved solids) have EC values of approximately 2300 mS/m (TDS in mg/L $\approx$ 6.4*EC in mS/m).

Factors affecting soil electrical conductivity

The EC of soil is controlled by how an electrical current passes through the soil matrix and influenced by a number of factors:

- porosity—the shape and volume of pores;
- permeability—the interconnectedness of pores through which fluids can flow;
- moisture content—the extent to which pores are filled with water;
- ionic species (chemical composition) of pore water;
- temperature and phase state (liquid/gas) of the pore water; and
- the amount and composition of colloids such as clays.

The measured EC of soil may be greater or less than the conductivity of the pore water. In soils with low salt content the effect of clays usually dominates, and the conductivity of a clay-rich soil can be an order of magnitude higher than the conductivity of the pore water. Conversely, in soils with high salt content the contribution to conductivity from the salt concentration generally outweighs that from its cation exchange capacity, and is relatively independent of the clay content. EM tools have been shown to be effective in mapping all salinity types, including 'dry saline land', where salinity is present above the watertable. Other studies in Australia have shown that between 75% and 90% of EC_a values can be usually explained by total soluble salt content.

Conversion of soil electrical conductivity to salinity—'calibration'

The success of deriving salinity values from EC measurements depends on the establishment of empirical equations that relate depth profiles of soil electrical conductivity of a saturated paste extract (EC_e) or soil water extract ($EC_{1:5}$) to bulk electrical conductivity (EC_a) obtained from EM measurements.

Numerous studies in Australia have derived calibration equations that work reasonably well in particular areas under constant hydrological conditions. However it should be noted that the volume of earth sampled by EC_e measurements on soil samples is much smaller than EC_a measurements from EM measurements. Variations in the salinity profile with depth—increasing, uniform or decreasing—can be determined by comparing vertical with horizontal orientations of ground EM conductivity tools from borehole EM logs or from inversion of broadband (wide frequency or time range) EM data. The term inversion is used to describe the general process (usually computer-based) of deriving a geologically plausible model of the subsurface that is consistent with observed data.

EC_a measurements in dryland soils are best made during the time of the year when soils are sufficiently moist to conduct electricity. It is inappropriate to try to infer salinity from measurements of EC_a made on dry or nearly dry soil, and also to include salinity analyses of such soils in the data used to establish EC_a versus EC_e calibrations.

The salinity of soil water (the water that is accessible to plants) may be much lower than that estimated from EC_e. This is because salts will often be present in the saturation-extract that would not be in solution under actual field conditions. Additionally, salts contained within the fine pores of aggregates will contribute to the EC_e value, although it is doubtful that significant amounts of such salts are absorbed by plant roots or affect the availability of most of the water extracted by the plant (which is primarily that present in the larger pores).

Shallow electromagnetic conductivity profiling with EM31.

Photo: Kate Wilkinson.

4. MAPPING SALINITY

An intimate relationship exists between the landscape, its geological and climatic history, weathered and transported soil types, groundwater, and the hazard posed by the salt load in the soil. Combinations of mapping techniques can be used to provide enhanced information on the operation of natural systems and to derive the geological and hydrological properties of the landscape—including soils, salt content and subsurface flow pathways.

The term 'salinity mapping' in its broadest sense encompasses a range of procedures that can be used to delineate the surface expression of salinity, give insight into how the salinity processes take place (inferring water flow), and resolve patterns of salt store. Integrated landscape mapping involves detailed regolith studies and palaeogeographic reconstruction to delineate the subsurface geology, regolith architecture and salt distribution.

This multidisciplinary 'geological systems' approach can be used to generate a three-dimensional picture of the subsurface and associated saline groundwater, salt stores and flow systems that deliver salts to the discharge site (see box). Detailed studies of the regolith using airborne geophysics and borehole investigations demonstrate that the subsurface has much greater variability than can be inferred from surface measurements. At catchment and subcatchment scale the effects of variability in the regolith are likely to be particularly significant in influencing salt store and local groundwater flow.

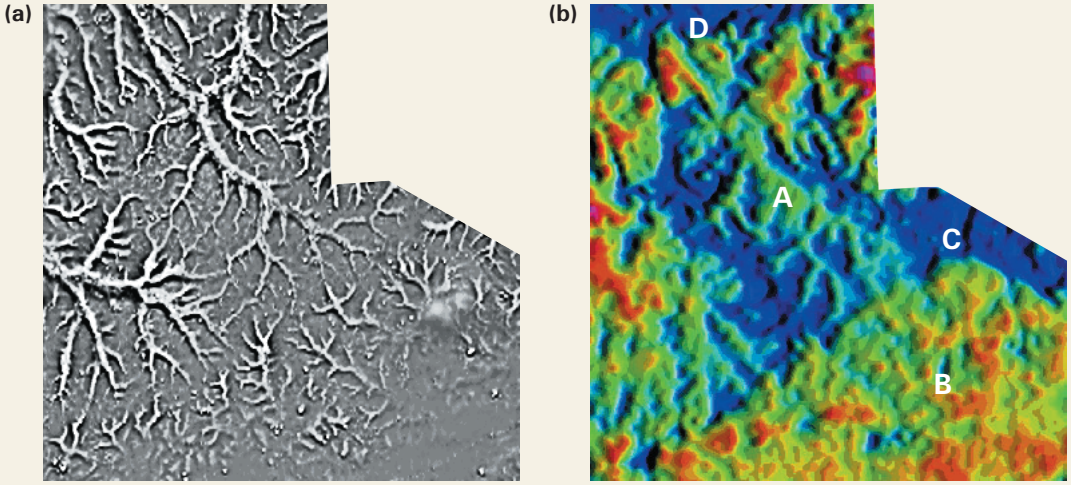
MULTIDISCIPLINARY APPROACH TO MAPPING

Airborne geophysical techniques can be used to map regolith units to give insight into the geological and hydrological processes. For example, aeromagnetics and airborne electromagnetics (AEM) can be used to map regolith units without considering 'conductivity' or 'salt-store'.

Although a magnetic map is predominantly an image of magnetic mineral concentrations in the subsurface, aeromagnetics is rarely commissioned to determine the quantities of magnetic minerals present. Instead, spatial patterns in magnetic minerals in the subsurface are used to delineate boundaries of geological units (see Figure 2a). The patterns from such imagery reveal the watercourses on the surface and buried palaeochannels where these coincide with appreciable amounts of magnetic mineral accumulation.

Similarly, AEM is often used to map regolith units through analysis of spatial patterns (see Figure 2b). This image of the same area shows buried channels (A), a distinct sub-basin (B), upland areas with thin regolith cover (C) and an east-west break in pattern (D) without the need to consider the possibility of salt stores.

Figure 2. (a) Greyscale magnetic image (first vertical derivative of total magnetic intensity) and (b) colour conductivity image (interval conductivity for 10 to 15 m below surface) where the warmer colours (red and magenta) indicate higher conductivity values (courtesy Richard Lane, Geoscience Australia).



Map quality and interpretation

Mapping methods and their interpretations form the basis of products that expand the knowledge base of non-experts, managers and policy makers. They should be assessed in the context of economic considerations (assets at risk, cost of data acquisition, cost of monitoring, consequence of doing nothing) in order to produce a salinity management plan.

Maps that have greater data input will be more complete. Mapping of larger areas will result in lower costs per hectare. Technological advances will also affect the suite of optimal techniques to provide each product.

Each mapping technique can be used for different purposes and end products, and a skilled interpreter will always combine as many different types of measurement as possible to produce an interpretation or mapping product. The user should also bear in mind the scale at which the data were acquired, and their accuracy and the inherent spatial resolution of the technique:

- ground measurements provide a more accurate measurement at one point in space (and at one time), but may not reflect the inherent geological variability unless measurements are taken at a high spatial density;
- airborne methods measure the average response over a 'footprint' controlled by the flying height and speed—thus aerial photos may be used for mapping at 1:5000 scale with centimetre resolution, whereas airborne radiometrics and electromagnetics have footprints (spatial resolution) of tens of metres; while
- satellite products have pixel (spatial resolution) sizes ranging from 1 m to greater than 10 m.

Maps have traditionally been presented on paper. Over the last decade the increasingly wide availability of computers and geographic information systems (GIS) has meant that high-quality maps are easy to generate and distribute in electronic form.

Map provenance

Maps should include all or most of the following information.

- Informative heading or title
- Prominent statement indicating the status of the map (typically—draft, published or restricted internal use)
- Technical description of the technique or techniques used to generate data for the map, and assumptions underlying the presentation used
- Data source and processing history (including processing parameters and software used)
- Statement indicating the original purpose of the map and warnings about appropriate use and limitations (may include statements of accuracy)
- Acknowledgment of the owner of the data and the owner of the map
- Scale, north point, date of creation, legend
- Name and contact details of those responsible for the map

Choice of method

The choice of mapping methods depends on scale, ground conditions, the problem at hand, the available expertise and budget. The optimal choice and combination of methods should be targeted at the specific problem to be addressed, discussed with experienced practitioners, and include detailed discussion of the optimum suite of methods, ground control, processing and interpretation.

Many methods can be used to collect information that is useful in assessing risk. Air photos and multispectral imagery from aircraft or satellites, for example, can map a number of useful parameters at the surface that affect our ability to predict groundwater movement—including vegetation type, streams, terrain and land use. However images of landscapes affected by drought, bushfire damage, green flush brought on by spring rains on black soils can be misleading or confusing.

Ground verification of mapping is essential and may include visual inspection, local soil sampling and borehole logging.

Ideally, a multi-stage and/or multi-phase approach starting with preliminary analysis using existing datasets for hazard and risk assessment as a 'scene setting' exercise should be used before undertaking detailed mapping. Existing data gathered over large areas (multiple catchment or at State/Territory level) can be examined to help prioritise key areas for more detailed investigations. Thus, a multi-stage/multi-phase approach may involve more than one phase of mapping over the area of interest. The first phase may involve one or more techniques and be preliminary in nature, followed by analysis, then a second targeted mapping survey concentrating on key areas.

Mapping should be undertaken in a systematic manner with techniques that operate at the appropriate scale. Regional investigation using airborne surveys, for example, should be followed with ground survey in areas of particular interest or concern.

KEY FEATURES OF AIRBORNE AND SATELLITE TECHNIQUES

- Airborne electromagnetics is the only airborne technique that can map salt stored below the root zone. It can detect, but not resolve, salt stored within the root zone.
- Airborne magnetics help us to understand and map the gross structures—faults, dykes and basement highs below the soil layer—that contribute to the movement of groundwater.
- Radiometrics (gamma-ray spectrometry) is useful for mapping soil type.
- Multiple airborne techniques can be combined in a single survey at considerable cost savings to flying surveys individually—AEM surveys usually include aeromagnetics, and an approximate DEM (digital elevation model) is a by-product of most modern airborne surveys.
- Emerging techniques such as airborne and satellite hyperspectral imaging and radar imaging are yet to be implemented operationally. As costs decrease and improvements in image analysis occur, airborne radar has increasing potential for operational use. Hyperspectral imagery requires further research before its operational potential can be further evaluated.
- Ground verification is essential.

Comparison of airborne and ground methods

When comparing airborne, ground and borehole results it is important to note that each technique has its own specific depth of investigation, horizontal footprint, and vertical and horizontal resolution. Differences in the volume of investigation and horizontal and vertical resolution thus affect the correlation of different techniques (see box next page).

The very accurate measure of soil properties such as salt content on small samples may be misleading when natural spatial (lateral and vertical) variations are considered. Techniques such as EM that are sensitive to large volumes of ground may not be as accurate or precise as point measurements, but will give a truer representation of average earth properties over a larger area.

Sampling groundwater.

Photo: Mark Glover. © CSIRO 2005. Reproduced with permission.

Airborne mapping with combined magnetics and radiometrics.

Photo: Fugro Airborne Surveys

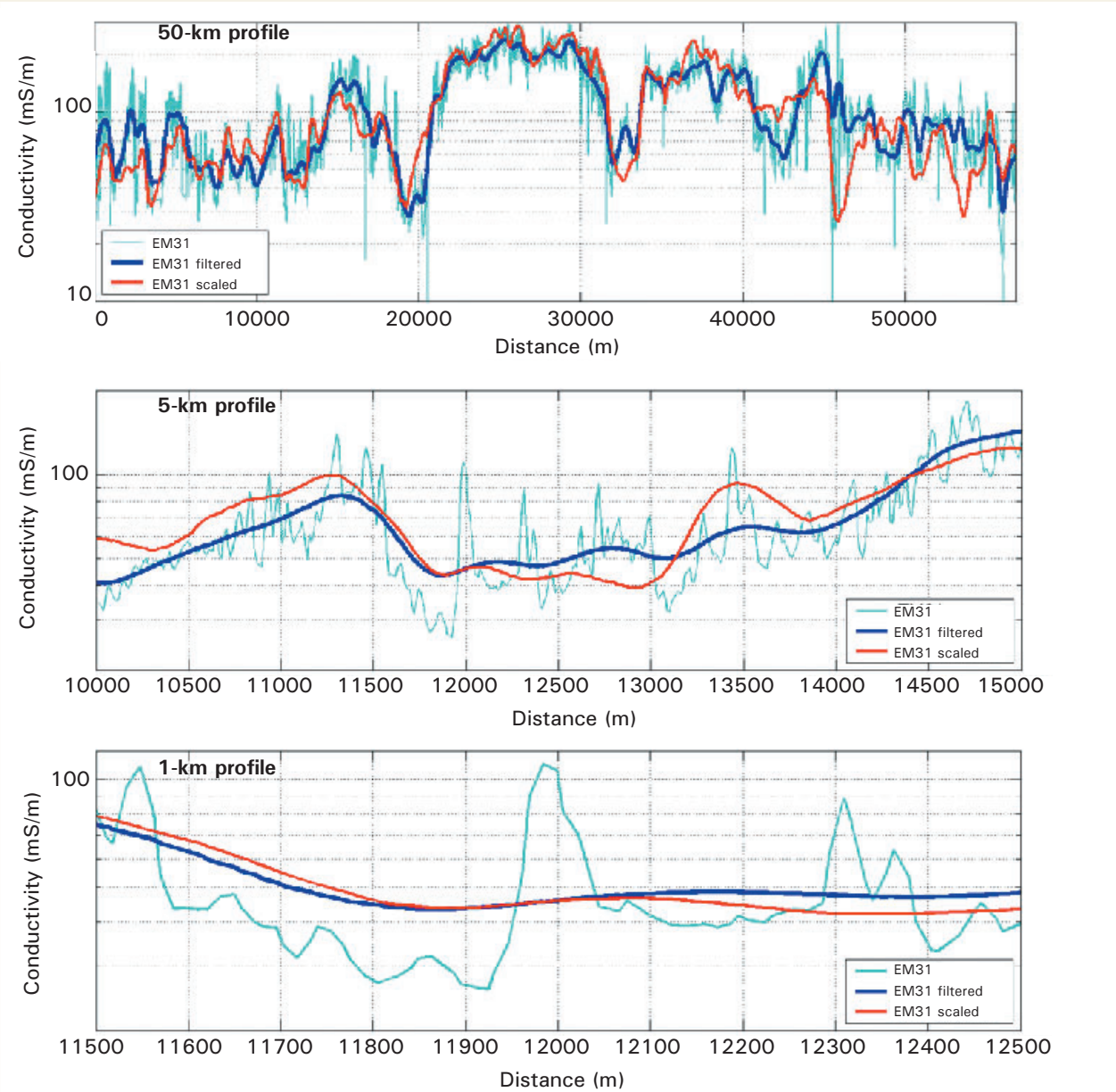
DIFFERENCES IN HORIZONTAL RESOLUTION

(example from St George in Queensland)

The following example shows differences in horizontal resolution as measured with ground (EM31) and airborne (TEMPEST) systems over profiles of length 50 km, 5 km and 1 km. Raw EM31 measurements are plotted in light blue, TEMPEST AEM conductivity predictions for 0 to 5 m below surface in red, and EM31 measurements filtered with a rolling average that mimics the lateral sampling of the AEM measurements over several hundred-metres in dark blue. The AEM and averaged EM31 measurements agree fairly well for all profile lengths. At broader scales represented by the 5 and 50 km profiles, the AEM predictions correlate moderately well with the trends in the raw EM31 measurements. However, over profile lengths that are little more than the horizontal resolution of the AEM system (e.g. 1 km) shown in the bottom panel, the broad averaging involved in the AEM measurements is unable to capture the local variability detected using an EM31 instrument. The AEM conductivity predictions and the raw EM31 apparent conductivity values would show very low correlation at this local scale.

Similar issues arise when comparing other types of measurements that sample different volumes, for example soil samples extracts, borehole measurements, surface and airborne measurements.

Figure 3. Profiles of apparent conductivity measured using an EM31 instrument in vertical dipole mode (light blue line), filtered EM31 apparent conductivity (dark blue line) and conductivity predictions for 0 to 5 m depth from TEMPEST AEM data (red line). (a) 50 km profile, (b) 5 km profile and (c) 1 km profile. Profiles prepared by Richard Lane (CRC LEME / Geoscience Australia) from data provided by the Queensland Department of Natural Resources and Mines, CRC LEME and the Bureau of Rural Sciences.



A STAGED APPROACH TO MAPPING

Before investing in a mapping project, it is important to first ensure that maximum use is made of existing information, ranging from local knowledge, existing maps and the regional context.

A multi-phase and/or multi-stage approach, where mapping alternates with ground-truth and interpretation, ensures that best use is made of the existing and new information, and that data are progressively transformed into useful information, and then into knowledge of salinity and landscape processes.

One effective mapping design may be to use an initial sampling approach that determines the likely location of salt in the study (e.g. field inspection, stream sampling), followed by techniques that map salinity on the surface (air photos, airborne imaging, and/or satellites), plus deeper probing techniques (e.g. AEM). At each stage, field observation (ground-truthing) should be used as an essential tool for calibration and interpretation, with borehole measurements as required. The final stage is some form of post hazard mapping. The cycle is then repeated at the next level of detail, each time targeted to answer specific questions.

This staged approach draws on the best elements of each available mapping technique and permits the best use of existing information. It will help target or prioritise the areas that require new mapping information.

RECOMMENDATIONS

- To map the extent of areas affected by dryland salinity the most straightforward methods are API (air photo interpretation) and satellite imagery combined with visual inspection, and electrical conductivity (EC) mapping using a ground induction conductivity meter.
- To map the presence of salt at depth (> 2 m) we recommend AEM constrained by borehole logging and point EC sampling.
- To investigate hydrological factors affecting the transportation of salt by groundwater, aeromagnetics and AEM are the key techniques.

5. MAPPING METHODS

Techniques listed in the following pages are mainly used for hazard mapping, although some useful data may be acquired at the same time for input into salinity risk assessment. Many of the techniques may only have marginal use for mapping the salt itself, but they may be essential for generating landscape, hydrological pathway and soil maps from which salinity risk and management information can be derived. Types of mapping are categorised by their depths of investigation into the subsurface,

Salt content, salt load and salt hazard

The terms 'salt content', 'salt load' and 'salt hazard' are often used interchangeably. Strictly speaking, salt content refers to the percentage (by weight) of salts contained in a sample of soil. Salt load is normally used in the context of the total amount of salt in the soil profile that can be potentially mobilised by water. Salt hazard refers to salt that can be moved to threaten an asset.

Costs

Mapping costs usually comprise:

- cost of initial survey design;
- cost of data acquisition (for ground and airborne surveys includes mobilisation/ demobilisation, and sometimes a standby cost in the event of bad weather);
- costs of data preliminary processing, ground-truthing and field calibration, final processing and interpretation; and
- cost of data verification to confirm the quality of the results.

The cost of mapping using various techniques included in the tables on the following pages relate to acquisition costs and in some cases preliminary processing. Total survey costs, including survey design, calibration and ground-truthing, and interpretation can often double these indicated costs.

Mention of a specific vendor or instrument in the following tables does not represent endorsement.

Sampling groundwater for laboratory analysis.

Photo: Pauline English. © CSIRO 2005. Reproduced with permission.

1. Laboratory analysis

Soil sampling followed by chemical analysis in the laboratory determines solute type and concentrations. Soil samples can be taken at the surface, as well as in the root zone or greater depths through augering or trenching. Field procedures involve the use of saturated paste extracts of soil samples and soil solution extracts, from which analytic procedures (e.g. cation analysis and anion analysis) can be performed. Similar techniques can be used for groundwater and water extracted from soil. Complete analyses of multiple chemical species can be obtained from analytical testing at commercial laboratories.

2. Total soluble salts measuring EC of soil pastes and extracts in the field

Total salt concentration can be estimated using a range of in situ or remote sensors including:

- aqueous extracts of soil samples;
- samples of water obtained from the soil or in boreholes; and
- through the use of buried porous salinity sensors that imbibe soil water and measure its electrical conductivity.

Other techniques include remote measurements of the electrical conductivity of bulk soil using four-electrode galvanic sensors or, more commonly, electromagnetic (EM) induction conductivity meters (see pp. 33).

APPLICATION TO HAZARD MAPPING	CONTRIBUTION TO RISK ASSESSMENT	COST	COMMENTS
1. LABORATORY ANALYSIS			
The most rigorous method of quantitatively evaluating soil salinity.	Basic knowledge of the amount and type of salt is an important parameter.	Standard water set of basic anions and cations ~ $100 – 200 per sample.	Laborious—days or weeks needed to obtain results. Salinity often varies substantially laterally and vertically, so samples may not be representative of a larger area unless sampling density is high. Salinity may also vary over time.
2. TOTAL SOLUBLE SALTS MEASURING EC OF SOIL PASTES AND EXTRACTS IN THE FIELD			
A common and useful field procedure, but ignores soil moisture content and mobility of salt.	Useful as an adjunct to other techniques.	Around $10 per sample for EC and pH.	Needs to be calibrated for solute type (laboratory analyses). Not all salt measured on paste extracts affects vegetation or is readily mobilised.

3. Visual inspection

Visual inspection identifies salt scalds and salt pans where salinity impact reach the ground surface. The presence of deeper salinity can sometimes be inferred from study of vegetation type and health. Note that vegetation can also be stressed by waterlogging, soil factors (sodicity, pH) and land use (over-grazing).

Visual inspection is an essential component of the calibration and validation process of other broadacre mapping techniques, and should also be included in any initial survey design.

APPLICATION TO HAZARD MAPPING	CONTRIBUTION TO RISK ASSESSMENT	COST	COMMENTS
3. VISUAL INSPECTION			
Directly observes salt scalds and stressed vegetation. Applicable to both surface and indirect root zones.	Provides spot checks for some attributes required for risk assessment (e.g. soils, vegetation type, geology and land use).	Subject to the cost of labour.	Useful technique for mapping small areas (paddocks). Essential for checking maps prepared from satellites, aircraft or systematic vehicle-based EM surveys. Ensures that the extensive local knowledge of landholders is used (e.g. changes of salinity outbreaks through time) as well as observations of causes/effects (e.g. wet seasons, floods).

Inspecting salt scalding at the base of steep cleared bedrock slope – Boho, VIC.

Photo: Pauline English. © CSIRO 2005. Reproduced with permission.

4. Aerial photo interpretation (API)

Aerial photo interpretation is the oldest remote sensing technique for broadacre mapping. It involves the systematic acquisition of photos from precision cameras mounted on aircraft. Salinity-related mapping usually involves the detection of visible salt on the surface or the identification of vegetation patterns or water-bodies that might infer salinity. API mapping can also delineate drainage lines (hydrology), landform, geology or geomorphology to help with an understanding of landscape processes for risk assessment. Images that are affected by drought, bushfire damage, green flush (such as spring rains) can be misleading.

5. Airborne video

Airborne video, largely experimental, is an extension of aerial photographs, and useful for examining flight paths for specific features.

APPLICATION TO HAZARD MAPPING	CONTRIBUTION TO RISK ASSESSMENT	COST	COMMENTS
4. AERIAL PHOTO INTERPRETATION			
Directly maps salt scalds. Indirectly maps stressed vegetation. Applicable to both surface and indirect root zones.	Substantial contribution as can also map vegetation type, streams, terrain, land use.	Each air photo costs around $50. An experienced interpreter can map 3 to 6 photos per day. Cost is approximately $1/ha (assumes existing air photos and interpretation at a scale of around 1:25 000). New digital photography costs $5 to $20/ha scale at 1:25 000 scale including analysis.	A well-established technique. Can be slow to cover large areas but very reliable for surface mapping. Digital photography is emerging as a replacement for traditional film, at cost per frame from $20 to $50 (minimum purchase often applies – approximately $2000).
5. AIRBORNE VIDEO			
Applicable although still only experimental. Applicable to the surface and indirect root zones.	Potential contribution as can also map vegetation type, streams, terrain and land use.	Cost $10 to $50/ha assuming new acquisitions at a scale of 1:25 000 including analysis.	Competes with the multispectral instruments for applications.

Aerial photo of saline land near Williams Creek, NSW.

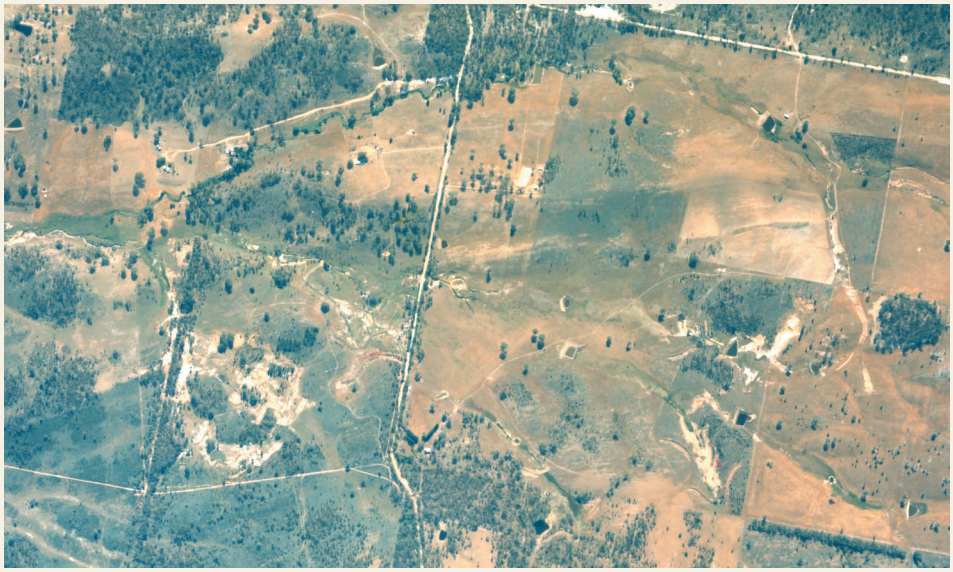


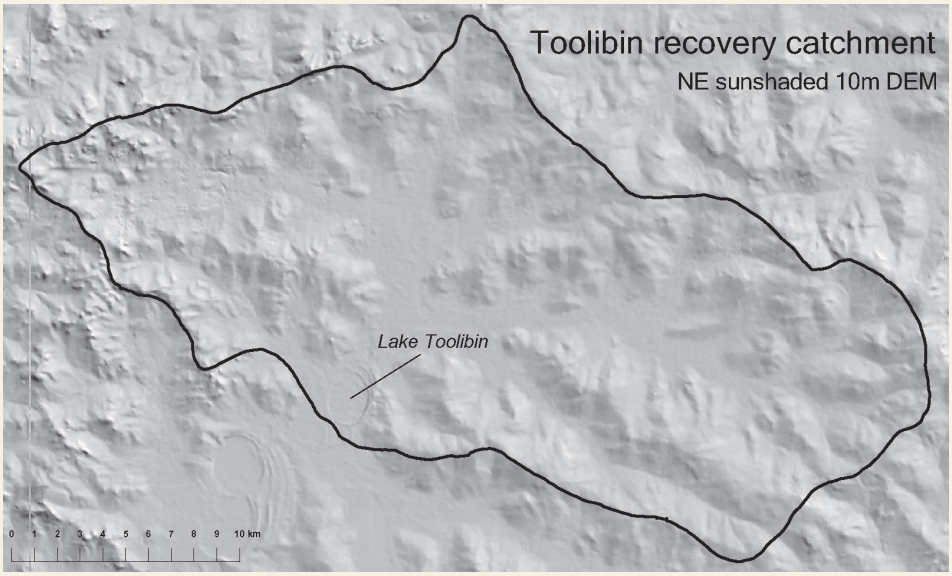
Photo: courtesy DIPNR NSW

6. Digital elevation models (DEM)

Digital elevation models (DEM) with accuracies of tens of centimetres can be derived from air photos by automated photogrammetric techniques. Alternatively, more accurate technologies for mapping topography such as airborne laser scanning (ALS), and the Airborne Laser Terrain Mapper (ALTM) are fast gaining acceptance.

APPLICATION TO HAZARD MAPPING	CONTRIBUTION TO RISK ASSESSMENT	COST	COMMENTS
6. DIGITAL ELEVATION MODELS (DEM) (FROM AIR PHOTOS, STEREO MULTISPECTRAL IMAGERY, AIRBORNE LASER, RADAR)			
Not relevant as DEM do not directly detect salt or groundwater. Applicable to the surface only.	Substantial contribution. Can infer drainage and seepage patterns.	Costs vary substantially depending on scale and level of detail. Large surveys < $0.3/ha.	The landscape context to spatial salinity patterns is invaluable in being able to enhance the final mapping quality and as a very important aid to follow-up management. DEM data is normally acquired simultaneously with airborne electromagnetics and with aeromagnetics.

Digital elevation model of part of the Toolibin Catchment, WA. The data have a accuracy of 10 m horizontally and 1 to 2 m in elevation. The image has been enhanced using virtual illumination from a north-easterly direction. The relative relief displayed by this grey scale image is approximately 50 m, with Lake Toolibin (300 ha) visible as a circular feature in the south-west corner. (Image courtesy Dr Richard George, WA Dept Agriculture)



7&8. Airborne and satellite radar

Radar techniques measure the complex reflectance of the Earth from electromagnetic radiation in the microwave (5.7 to 68 cm or 5.3 to 430 MHz) range by transmitting an active pulse from an aircraft or satellite platform. Radar signals are affected by moisture content and surface electrical conductivity and to a lesser extent the chemical composition of the soil. Airborne and satellite radar has been used in research trials for salinity mapping. Most radar systems give very little penetration of the surface and generally do not see into the root zone. They require relatively moist ground conditions across the area to be mapped and the radar signal can be confused by the overstorey vegetation.

Airborne and satellite-based radar systems can also produce digital elevation models of high quality over large areas. The NASA Shuttle-based mapping systems known as the Shuttle Radar Topography Mission used the Space Shuttle Endeavour to acquire radar data over 80% of the Earth's surface in February 2000. The conversion of these data into a DEM are now virtually complete and the data will be released by NASA. The on-ground resolution of the data are 30 m by 30 m pixels and the vertical accuracy is about 16 m.

APPLICATION TO HAZARD MAPPING	CONTRIBUTION TO RISK ASSESSMENT	COST	COMMENTS
7. AIRBORNE RADAR (e.g. AIRSAR)			
Suitable through indirectly mapping surface electrical conductivity for radar wavelengths greater than 6 cm. Applicable from the surface to several metres.	Radar has the ability to map very accurately the terrain surface (DEM) at fine resolution over large areas.	Around $5 – $15/ha. Even small areas may cost $1000s due to the cost of acquiring the imagery and the software required to process it (one-off cost).	Largely an experimental technique at present with potential application for salinity mapping. Has potential to be used as a tool for creating DEM which could therefore contribute to risk assessments.
8. SATELLITE RADAR (e.g. SIR-C & D, JERS -1, SRTM)			
Possibly useful through indirectly mapping electrical conductivity of surface and subsurface where radar wavelengths exceed 6 cm. Applicable to between 10s and 100s of centimetres only.	Has the ability to map the terrain surface (digital elevation models) at fine resolution over large areas very accurately.	Not meaningful to quote cost per hectare. Even small areas will cost $1000s due to the cost of acquiring the imagery and the software required to process it.	Satellite radar has no proven operational use for salinity hazard mapping at present although it does offer potential. However it will make a solid contribution to the mapping of topography which helps understanding of risk assessment. NASA will be releasing over the next couple of years the Shuttle Radar Topographic Mission mapping that will produce a worldwide DEM and topographic maps for the first time.

9–12. Airborne and satellite imaging spectrometry

Imaging spectroscopy measures reflected sunlight in the visible to short-wave infrared (0.4 to 2.5 microns in wavelength) and emitted blackbody radiation in the thermal infrared (8 to 12 microns in wavelength) regions of the electromagnetic spectrum, to create images of the surface of the Earth. Such measurements can be made from aircraft or satellites and can cover large areas at high resolution.

By measuring this complex spectra of signals, it is possible to map vegetation types and infer effects of stress, particularly patches of vegetation that are adversely affected by the presence of dryland salinity in the root zone. Also under ideal conditions it is also possible to infer mineralogy of iron oxides, sulphate, hydroxyl and carbonate mineral assemblages and, by association, surface salinity. However ground control and local knowledge are important for interpretation of spectrometry data and images that are affected by drought, bushfire damage, green flush (such as spring rains) and occur on black soils (leads to mapping confusion) can be misleading or confusing.

Satellite and airborne systems can now resolve areas of just a few metres square in size on the surface of the Earth. They can cover tens of thousands of square kilometres in a single pass and repeat that pass every day.

APPLICATION TO HAZARD MAPPING	CONTRIBUTION TO RISK ASSESSMENT	COST	COMMENTS
9. AIRBORNE IMAGING: MULTISPECTROMETRY (e.g. CASI)			
Suitable through directly observing salt scalds or indirectly mapping stressed vegetation. Applicable to the top few centimetres and the indirect root zone.	Substantial potential contribution as imagery can also map vegetation type, streams, terrain and land use.	$10 to $50/ha (assuming new acquisitions at a scale of 1:25 000) including analysis. Even small areas will cost $1000s due to the cost of acquiring the imagery and the software required to process it (one-off cost).	Little used due to the substantial cost of acquiring the imagery and processing it to produce maps. Has potential.

False-colour hyperspectral (HyMap) image of part of the Coleambally Irrigation Area, NSW: vegetated paddocks are red; stubble is white; bare soils are green.

Source: Courtesy Tim McVicar and Tom Van Niel, CSIRO Land and Water and Cooperative Research Centre for Sustainable Rice Production. The acquisition of the HyMap image was supported by the Hyperspectral Task of the CSIRO Earth Observation Centre.

APPLICATION TO HAZARD MAPPING	CONTRIBUTION TO RISK ASSESSMENT	COST	COMMENTS
10. AIRBORNE IMAGING: HYPERSPECTROMETRY (e.g. HYMAP, AVIRIS)			
Suitable through directly observing salt scalds or indirectly mapping stressed vegetation. May also infer salt by known association with specific mineralogies. Applicable to the top few centimetres and indirect root zone.	Substantial potential contribution as imagery can also map vegetation type, streams, terrain and land use.	$10 to $50/ha (assuming new acquisitions at a scale of 1:25 000) including analysis. Even small areas will cost $1000s due to the cost of acquiring the imagery and the software required to process it (one-off cost).	A new technology still in the research phase; resolving ability higher than multispectral imagery.
11. SATELLITE IMAGING: MULTISPECTROMETRY (e.g. LANDSAT, SPOT, IKONOS, EARTHWATCH)			
Suitable through directly observing salt scalds or indirectly mapping stressed vegetation. May also infer salt by known association with specific mineralogies Applicable to the surface and indirect root zones.	Substantial potential contribution as imagery can also map vegetation type, streams, terrain and land use.	Usually much less than one cent per hectare. Minimum area purchases usually apply so costs can typically run to $100s plus processing and interpretation.	Proven technique for near-surface salinity hazard mapping in the hands of skilled interpreters in some regions. Well developed for its contribution to risk assessment (e.g. Western Australia Land Monitor).
12. SATELLITE IMAGING: HYPERSPECTROMETRY (e.g. HYPERION)			
Suitable through directly observing salt scalds or indirectly mapping stressed vegetation. Experimental only at this stage. Offers potentially greater mapping accuracy than the multispectral instruments. Applicable to the surface and indirect root zones.	Substantial potential contribution as imagery can also map vegetation type, streams, terrain and land use.	Minimum purchase of 42 km x 30 km for approximately $3000. Cost $5 to $50/ha including processing.	Represents a new and significant improvement in technology (cf multispectral sensors). Requires substantial research before it develops proven applications. Likely to have broader applications than the multispectral instruments. Price set by vendors will in part determine the degree of uptake by users.

False-colour 2.5 m resolution SPOT5 image near Boorowa, NSW, November 2003 (©CNES 2003).

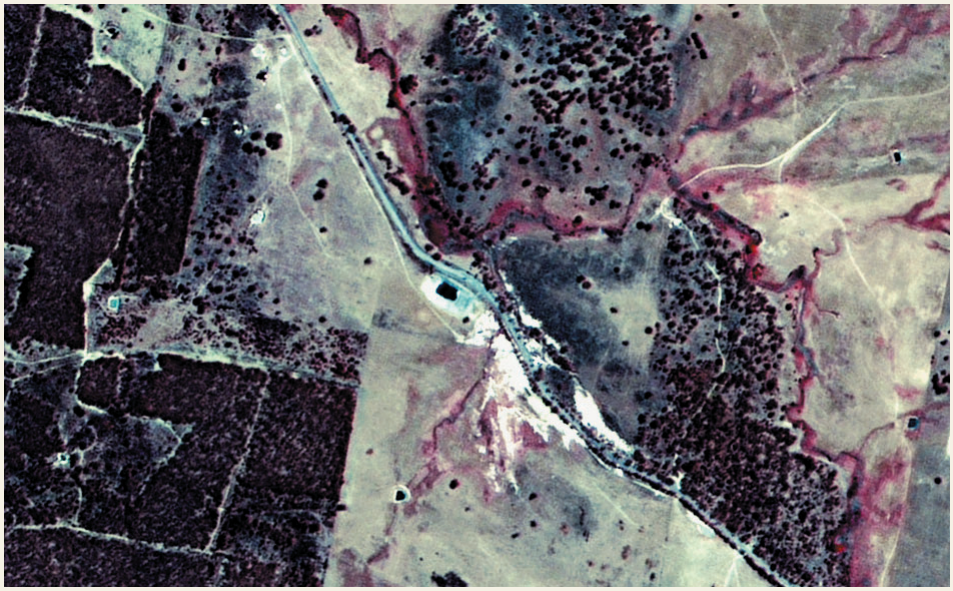


Image courtesy Spot and Raytheon

13. Airborne and ground gamma-ray spectrometry (radiometrics)

Gamma-ray spectrometry, commonly known as radiometrics, is based on measurement of naturally occurring gamma rays emanating from potassium-, uranium-, and thorium-bearing materials at the Earth's surface. Gamma-ray spectrometry is widely used for soil mapping and can be measured either from aircraft or, more rarely, from vehicles on the ground. Since surface salinity is often correlated with soil type and landscape characteristics, radiometrics is sometimes used as a tool for (very) indirect mapping of surface salinity and recharge properties, especially when combined with DEM.

APPLICATION TO HAZARD MAPPING	CONTRIBUTION TO RISK ASSESSMENT	COST	COMMENTS
13. AIRBORNE AND GROUND GAMMA-RAY SPECTROMETRY (RADIOMETRICS)			
Provides mapping of soil types that sometimes correlate with salinity. Applicable to the top 10s of centimetres only.	Able to produce quality soil mapping.	Airborne: < $1/ha, depending on area. Ground: $10 to $20/ha.	Airborne or ground. A demonstrated technique for broad area soil mapping that is showing great promise operationally, especially when combined with DEM. Requires specialist analysts for interpretation. Claims about its ability to directly map near surface salinity do not have scientific foundation.

High-resolution acquisition of airborne magnetic and radiometric data – WA.

Photo: Fugro Airborne Surveys

14. Shallow electromagnetic conductivity mapping

Lightweight portable ground conductivity meters have achieved widespread acceptance for salinity mapping in the root zone and are now an important part of land and water management.

These instruments are designed for ease-of-use and provide a direct readout of electrical conductivity. They have a focused depth range extending over the root zone to depths of several metres. The instruments can be used in two measurement configurations (horizontal and vertical coils), from which some information can be obtained of variation in conductivity with depth (e.g. increasing, decreasing or constant through the root zone).

Since single measurements with conductivity meters have a relatively fixed depth of investigation, some users have devised 4-wheel bike- or vehicle-mounted, semi-automated systems that employ a combination of coil configurations or systems with different coil spacings to provide better depth information and more rapid coverage of larger areas.

The systems are also used in time-lapse mode to determine soil salinity changes for salinity risk or remediation applications. They have been used in many areas of Australia to determine large-scale root zone soil salinity classes.

Electrical conductivity is strongly correlated with salinity; however other factors such as soil moisture content, soil texture and composition (in particular the amount and type of clays) and temperature can also affect the readings and corrections should be made for these parameters.

ELECTROMAGNETIC DEFINITIONS

Frequency domain systems are those that transmit a continuous sinusoidal waveform, and measure the phase and amplitude (or in-phase and quadrature components) of the resultant signal.

Time domain systems transmit a square or half-sine wave pulse, and measure the amplitude of the resultant decaying (or transient) signal at various times after cessation of the transmitter pulse.

Conductivity (electrical) is the ability of material to conduct electrical current. Units are siemens per metre (S/m) or more commonly millisiemens per metre (mS/m).

Resistivity is the reciprocal of conductivity. Resistivity (units in ohm-m) is commonly measured with direct current (DC) electrical probing devices.

Apparent conductivity (EC_a) is the conductivity of a uniform earth (averaged to the depth of investigation) that would give the same EM response as that measured. Apparent resistivity, ρ_a, is the reciprocal of apparent conductivity.

Skin depth describes the attenuation of electromagnetic fields as they diffuse into a conductive earth. It is defined the depth at which an electromagnetic field is attenuated to 37% of its value at the surface of the earth. Skin depth is given by the expression

$$\delta = 500\sqrt{\frac{R}{f}}$$

where *R* is the resistivity of the earth (equal to 1/EC) and *f* is the operating frequency. Lower frequencies penetrate to greater depth.

Diffusion depth at time *t* is analogous to skin depth in the time domain, replacing *f* in the expression by *1/t.* Later sample times penetrate to greater depths.

Low induction-number EM instruments operate over a certain range of transmitter-receiver coil separation and frequency parameters where the depth of investigation is controlled mainly by the separation between the transmitter and receiver coils rather than the operating frequency. Also known as conductivity meters (e.g. EM31, EM38).

Conductance is the product of conductivity and thickness of an electrically thin conductive layer.

DC (direct current) electrical 4-electrode measurements

Electrical conductivity (or more correctly its reciprocal, resistivity) can be also measured with DC electrode devices that require galvanic (electrical) contact with the ground. Although DC resistivity measurements are slower than those made with inductive conductivity devices, they are capable of improved depth resolution if measurements are made at a variety of electrode spacings.

APPLICATION TO HAZARD MAPPING	CONTRIBUTION TO RISK ASSESSMENT	COST	COMMENTS
14. SHALLOW ELECTROMAGNETIC CONDUCTIVITY MAPPING (e.g. GEONICS EM31, EM38)			
Strong correlation with salinity. A popular inexpensive method for mapping spatial variations in conductivity in the root zone at farm scale. Applicable to the root zone only.	Useful in mapping near-surface variability and salt load.	Starts at approximately $1500 per day. Coverage is between 50 ha/day (detailed grid) to 500 ha/day (>100 m lines) at roughly $1 to $30/ha.	Some depth information from varying coil orientation. Moisture variations and clay content are second-order effects. Should be calibrated at key locations.

Shallow conductivity measurements with EM38.

Photo: Kate Wilkinson

15&16. Surface-based electromagnetic and electrical depth sounding

A large number of instruments for measuring electrical conductivity at depths greater than 2 m are available, ranging from larger-spacing terrain conductivity meters, through transient electromagnetic (TEM) to DC-resistivity 4-electrode or array devices. Only a few of these have been used in Australia for groundwater and salinity investigations. Many of these techniques are eminently suitable for mapping salinity and landscape variations within the regolith, and can penetrate to depths of tens or hundreds of metres.

Mapping products include sections or maps of 'apparent resistivity' at a particular sample time, frequency or electrode spacing. Automated computer inversion routines can be used to produce depth sections and profiles of conductivity or resistivity.

APPLICATION TO HAZARD MAPPING	CONTRIBUTION TO RISK ASSESSMENT	COST	COMMENTS
15. SURFACE-BASED ELECTROMAGNETIC AND ELECTRICAL DEPTH SOUNDING: DEEPER-PROBING EM (e.g. GEONICS EM31, EM34-3, PROTEM, SMARTEM, TINYTEM)			
Useful in mapping salt stores beneath root zone to the regolith.	Can be used at broader scales. Also to map groundwater pathways and bedrock topography.	More expensive than shallow mapping. $2000 per day for 30 to 40 soundings. Profiling 20 to 30 line-km per day, processed data $300 per line-km. Assuming a line spacing of 200 to 400 m gives a cost of $6 to $15/ha.	Cannot resolve conductivity changes in root zone (with exception of EM31). Use in conjunction with shallow-probing EM.
16. SURFACE-BASED ELECTROMAGNETIC AND ELECTRICAL DEPTH SOUNDING: ELECTRICAL RESISTIVITY PROBING (e.g. ABEM TERRAMETER, GEOMETRICS OHMMAPPER)			
Capable of resolving vertical and horizontal variations in conductivity, from surface to bedrock. Applicable from the surface to the bedrock.	Useful for detailed mapping of groundwater pathways and bedrock topography.	$1400 for several km profiling per day. Resistivity imaging: 1 to several line-km per day; $3000 to $5000 per processed line-km. Assuming line spacing of 200 to 400 m gives a cost of $60 to $250/ha.	Requires use of grounded electrodes and towed arrays. Robust automated inversion software available to produce conductivity depth section. Higher resolution than deep EM.

17. Borehole conductivity logging

Borehole conductivity meters operate on the same principle as surface-based conductivity meters. Output units are in mS/m. Borehole conductivity logging provides excellent 'ground-truth' of the true conductivity of the ground versus depth, and should always be used to calibrate airborne electromagnetic soundings and surface-based electromagnetic and electrical depth soundings.

APPLICATION TO HAZARD MAPPING	CONTRIBUTION TO RISK ASSESSMENT	COST	COMMENTS
17. BOREHOLE CONDUCTIVITY LOGGING (e.g. GEONICS EM39)			
Ideal method for measuring conductivity versus depth in situ for salt store versus depth. Applicable below the root zone	Useful for understanding changes with depth.	Usually charged on daily basis; most instruments owned by consultants or government agencies. Approximately $2000 per day, for up to 10 bores per day.	Boreholes should be logged as a matter of routine. Important to map salinity profile and for calibration of surface and airborne systems.

Down-hole electromagnetic conductivity logging using the EM39.

Photo: Pauline English. © CSIRO 2005. Reproduced with permission.

18. Airborne electromagnetics (e.g. Tempest, Dighem, Resolve)

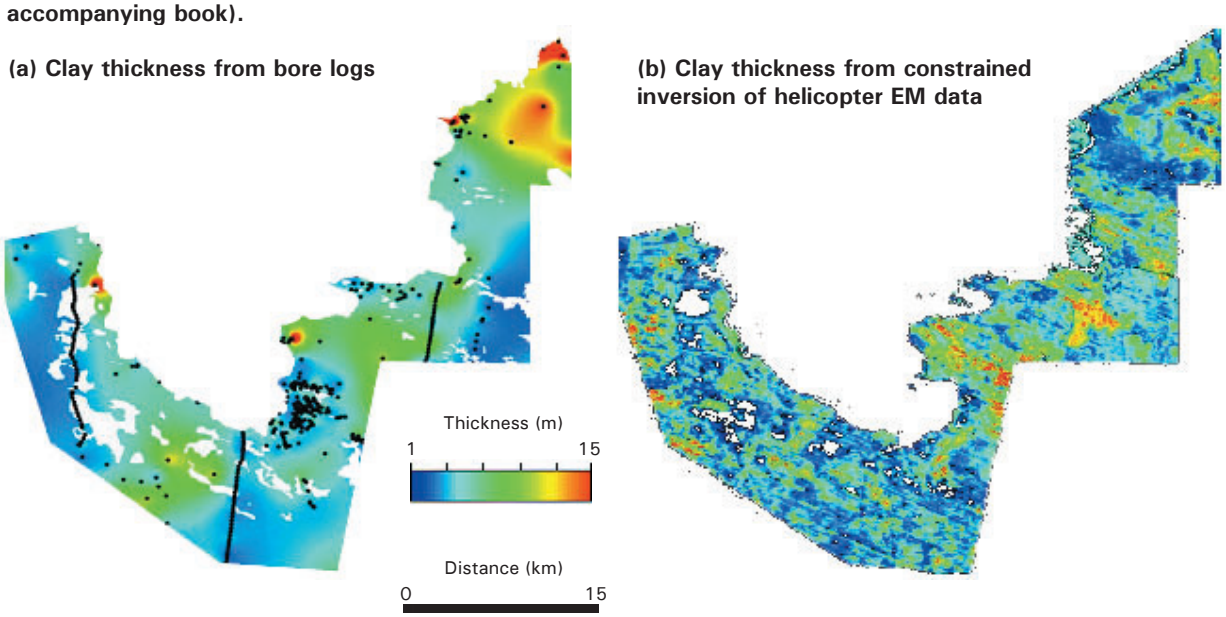
Of all the airborne geophysical techniques (aeromagnetics, radiometrics and electromagnetics), only electromagnetics (EM) has a signature closely related to salt stored below the subsurface. Airborne EM systems can be used from fixed-wing aircraft or helicopters (AEM or HEM) and are similar in many respects to the ground EM systems. Fixed-wing surveys (AEM) are generally preferred for larger areas and deeper depth penetration, while HEM surveys offer finer spatial resolution. Magnetic and digital terrain data are usually obtained at the same time as AEM.

The depth of investigation varies with ground conductivity—at best it is around one skin depth or diffusion depth—but it can be less depending on signal and noise levels. The footprint (or lateral averaging) of HEM systems is smaller than that of fixed-wing TEM airborne systems, especially in the shallow subsurface.

The fundamental limitations of resolution of inductive electromagnetic techniques (related to the volume of ground that contributes to each measurement) means that AEM systems can detect, but usually not resolve, conductivity distribution in the top 5 to 10 m.

APPLICATION TO HAZARD MAPPING	CONTRIBUTION TO RISK ASSESSMENT	COST	COMMENTS
18. AIRBORNE ELECTROMAGNETICS			
AEM is the only regional technique that maps salinity through the regolith and can also map total salt store. Applicable from the root zone through to bedrock.	Useful for mapping palaeochannels, basement topography and other pathways for groundwater flow.	From less than $1/ha, to more than $10/ha depending on line spacing, size and location of area.	Cannot resolve vertical variations within the root zone. Depth range depends on ground conductivity. Must be calibrated with ground and borehole data. Care must be taken with processing and interpretation products.

Thickness of clay unit in Riverland, SA, inferred from (a) bore holes and (b) helicopter electromagnetics. The detailed structure of clays and buried sand dunes is evident from the helicopter data (from Case Study 2 in accompanying book).



AEM capabilities and interpretation products

The main requirements of an AEM mapping system are broad bandwidth and accurate, calibrated data over the entire range of frequencies or sample times. A number of current research projects are directed at improving the near-surface resolution of AEM.

Interpretation or mapping products include apparent conductivity maps at each frequency or sample time; approximate conductivity-depth image (CDI) sections or depth slices and layered-earth inversion (LEI) and conductance maps. Care should be taken with the application of rapid imaging routines for processing and visualising AEM data, especially with inferred depth values. Estimates of accuracy and errors should always be given. Ground-truthing (through borehole induction logging or ground EM or electrical depth sounding) should always be used to calibrate AEM data.

Inversion and processing of airborne electromagnetics

Processing and interpretation of geophysical surveys, especially airborne electromagnetics, is complex because the signal originates from a range of depths. The conversion of raw data to a final depth image involves a number of steps, each having specific mathematical and physical assumptions:

1. *acquisition-calibration* of parameters such as transmitted waveform, filter settings, amplifier characteristics, and the geometric relationship between source and receiver;
2. *basic processing-correcting* for variations in acquisition parameters during the survey, including height corrections, geometric corrections and primary-field corrections;
3. *conversion to a conductivity-depth image* (CDI), a mathematically complex procedure with many approaches, each with its own assumptions, advantages and disadvantages (e.g. LEI, which assumes a fixed number of distinct horizontal layers; smooth-model inversion, where the conductivity is assumed to vary smoothly with depth; conductance maps and interval conductivity that give the average conductivity over a depth range; and approximate CDI sections);
4. *interpretation with geological constraints* involving converting conductivity-depth data to more relevant parameters (e.g. salt content as a function of depth and lateral position), in addition to structural interpretation of depth to bedrock and identification of stratigraphic and structural features. Interpretation requires sound knowledge of the local geomorphological and landscape properties, constrained by ground and borehole observations.

AEM conductivity data draped on topography, with depth slices.

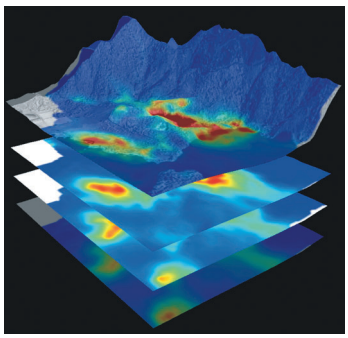


Image courtesy Fugro Airborne Surveys

Helicopter-mounted AEM system for higher resolution surveys.

Photo: Fugro Airborne Surveys

Recommendations for users of AEM

The following questions should be asked in the process of contracting an AEM survey and processing:

- *Have the target parameters (lateral extent, depth and conductivity range) been defined?*
- *Has the survey been designed to answer the question at hand, using the most appropriate system and acquisition parameters?*
- *Does the budget include the full cost of the survey including pre-survey planning, data acquisition, preliminary processing, ground-truthing, final processing and interpretation?*
- *Has the client clearly specified what is expected of the contractor? Are these spelt out in a tender specification sheet (such as issued by Geoscience Australia for its mapping surveys)?*
- *Does the client have access to staff with sufficient expertise to ensure that the survey and processing specifications are met?*
- *Are the mapping products clearly labelled with processing parameters, error estimates and details of the calibration process (if any)?*

19. Airborne magnetics

Airborne magnetics is an inexpensive technique normally acquired with other airborne data such as radiometrics or flown expressly for geological mapping. It is useful in mapping geological structures such as faults, dykes and basement highs below the soil layer that contribute to the movement of groundwater. Aeromagnetics can also be used to map buried channels (palaeochannels) if the sediments contain magnetic minerals above background levels (see Figure 2, p. 18).

APPLICATION TO HAZARD MAPPING	CONTRIBUTION TO RISK ASSESSMENT	COST	COMMENTS
19. AIRBORNE MAGNETICS			
Used for geological mapping, especially through soil cover. Applicable from the surface through to bedrock.	Useful for its ability to map gross features (such as palaeochannels, faults, dykes, and basements highs) in the landscape that strongly influence groundwater movement.	Less than a $1/ha.	Excellent method for mapping factors that contribute to better risk assessment; well proven in most landscapes. Requires specialist interpretation. Cost-effective contribution to risk assessment and salinity management.

20–25 Other ground-based subsurface mapping methods

A range of other methods have application in specific circumstances. Conductivity measurements on samples of water in streams and rivers can indicate locations of sources of salinity seeping into the watercourse from adjacent land.

Ground-probing radar (GPR), nuclear magnetic resonance (NMR), seismic reflection and refraction, seismo-electric and ground magnetics all have specialist application (see table) and have use in research programs but are not widely employed.

APPLICATION TO HAZARD MAPPING	CONTRIBUTION TO RISK ASSESSMENT	COST	COMMENTS
20. STREAM SAMPLING			
Provides an indication of salt stores that have entered the catchment upstream of the sampling location. Applicable to indirect surface and subsurface.	Provides evidence of mobilisation of salt.	An EC meter: $100 to $2000. Thousands of hectares can be covered relatively quickly depending on road access and density of streams and rivers.	This method is an indirect indication of land salinity but provides a useful trace-back mechanism to salt store and lateral flow into streams. Continuous profile can also be made in streams with towed EC arrays. The method is easily applied by land managers and community groups.
21. NUCLEAR MAGNETIC RESONANCE (NMR)			
Detects water content in soil profile versus depth. Applicable to the top 10s to 100s of metres.	May be useful in specialised studies when detailed knowledge of hydrology is required.	$3000 per day for 5 to 8 soundings at specific locations. Cost per hectare not meaningful.	Also known as magnetic resonance imaging. One sounding per hour, alternative to drilling and flow testing stratigraphic layers.
22. SEISMIC REFRACTION AND REFLECTION			
Maps subsurface stratigraphy. Applicable to the surface to sub-bedrock.	May be useful in specialised studies to map soil thickness, palaeochannels, flow paths, barriers, etc.	$2000/day for 1 – 3 km profile. Refraction 10 spreads/day around 100 m each. $3000 per processed line-km. Cost per hectare not meaningful.	Common tool in engineering and geotechnical studies. Not recommended for general use for salinity studies.

APPLICATION TO HAZARD MAPPING	CONTRIBUTION TO RISK ASSESSMENT	COST	COMMENTS
23. SEISMO-ELECTRIC			
Detects hydraulic conductivity (moveable pore water) in sediments. Applicable to the top 10s of metres.	Potential for research tool such as when detailed knowledge of hydrology is required.	Research mode costs $2000 to $3000/day. Cost per hectare not meaningful.	Very much experimental and not recommended for routine use.
24. GROUND MAGNETICS			
Used for geological mapping, especially through soil cover. Applicable from the surface through to bedrock.	Can be used to map features in the landscape (e.g. faults, dykes and basement highs) that influence groundwater movement.	Reasonably inexpensive: up to $1500/day or $10 to $200/ha depending on line spacing. Rental plus operator: $100 + $200/day ~ 15 to 20 km per day.	Ground variant of common airborne technique. Can be carried or mounted on 4-wheel bike with EM31.
25. GRAVITY			
Maps variation in bulk density of soil and rock in the subsurface.	Can be used to map features (e.g. faults, dykes and basement highs) that influence groundwater movement.	Moderately expensive: at 20 m spacing microgravity, 100 stations cost $2000. $1000s/ha.	For specialist use only.

26 Multi-stage and multi-phase mapping

A multi-phase or multi-stage approach, where mapping alternates with ground-truth and interpretation, ensures that best use is made of the existing and new information. This staged approach draws on the best elements of each available mapping technique and permits the best use of existing information. It will help target or prioritise the areas that require new mapping information and recognises that the most effective mapping design uses sequential field observation, analysis of existing data, hypothesis setting and testing with new mapping data.

APPLICATION TO HAZARD MAPPING	CONTRIBUTION TO RISK ASSESSMENT	COST	COMMENTS
26. MULTI-STAGE AND MULTI-PHASE MAPPING			
Suitable. Methods include mapping of surface salt and the deeper subsurface, followed by post hazard mapping verification.	Useful. Risk data sources and systems could include: GIS-based hydro-geology and geoscience data, natural resource data, land use data, groundwater flow systems, Flowtube and DEM.	Variable depending on size of area to be covered, resolution of mapping and combination of systems used.	A combination approach should always to be considered, particularly after reviewing existing data.

A towed conductivity streamer on a canal.

Photo: David Allen.

METHODS FOR PREDICTING SALINITY RISK

Most methods for predicting the risk to an asset from an increasing salinity hazard are based on statistical techniques or hydrological models. Examples of risk assessments using landscape modelling are provided in catchment case studies carried out for the National Land and Water Resources Audit. These studies were set in the context where the most appropriate data for answering the questions of stakeholders were not readily available, and the methods used were adapted for the best available data and optimal approach.

A review of modelling systems used in dryland salinity risk assessment and management forecasting was undertaken by NDSP. The *Practical Guide of Salinity Models* (PRISM) study, released on CD, reviewed over 300 tools, models and frameworks (see <www.ndsp.gov.au>).

Methods for estimating dryland salinity risk vary with the level of sophistication and data requirements, and include composite index methods, strongly inverse methods and trend based methods. Composite index methods rely on user experience, strongly inverse methods rely on statistical relationships and trend-based incorporate objective data on temporal changes. All of the methods can be applied in a spatial framework using GIS and used to prepare maps of areas predicted or hypothesised to be at risk of dryland salinity. However confidence in outputs of the methods varies considerably, with trend-based methods generally providing the highest confidence.

Mapping methods available in Australia, and their relative level and type of use.[1]

Method	Use in mapping dryland salinity	Use in mapping salt store	Use in mapping regolith & hydrology	Paddock scale	Farm scale	Catchment scale	Regional scale	National scale
SURFACE								
Visual	***	–	***					
Laboratory	**	–	–					
Radiometrics – ground	–	–	*					
Radiometrics – airborne	–	–	**					
Air photo interpretation	***	–	**					
DEM	–	–	***					
Multi spect (CASI etc.)	–	–	–					
Hyperspectral airborne	–	–	–					
Video	–	–	–					
Satellite imagery	***	–	*					
Hyperspectral satellite	–	–	–					
ROOT ZONE (< 2 m)								
Shallow EM	**	***	–					
Resistivity (Wenner, etc.)	–	–	–					
Field/drilling, etc.	–	***	***					
Airborne radar	–	–	–					
Satellite radar	–	–	–					
DEEPER (> 2 m)								
Deeper EM31/34 etc.	*	**	*					
Elect resist probing	–	*	–					
Stream sampling	–	**	–					
GPR	–	–	–					
NMR, seismo-electric	–	–	–					
Magnetics	–	–	***					
Gravity	–	–	–					
Borehole logging	–	*	–					
AEM	*	***	***					

*** commonly used

** less often used

* some use

– not applicable

1 Based on a table prepared by Richard George, WA Department of Agriculture

6. CONCLUDING REMARKS

This user guide presents a broad overview of methods for mapping salinity in the landscape, and assessing salinity hazard and risk. The concepts and techniques described here are covered in much greater detail in the accompanying book. The report also contains case studies that show examples of the use of multiple mapping techniques for mapping salinity in Australia at various scales. An extensive reference list, and detailed appendices that describe the capabilities and limitations of each technique, are also included in the book.

Dryland salinity is but one expression of the impact of human endeavour on the environment. Mapping techniques such as those described in the user guide and book can help unravel the complexity and interaction of landscape features, soils, water and salt and nutrient loads that define the environment, and assist in the development of sustainable land management practices.

Saline land affects a wide range of stakeholders.

Photo: Pauline English. © CSIRO 2005. Reproduced with permission.

UNITS

A variety of units are used for measures of salinity and electrical conductivity. The international standard (SI) unit for conductivity is S/m, and common EM instruments are calibrated to read mS/m. EC_e units are commonly quoted in dS/m or μS/cm. For this report, the unit mS/m will be used (100 mS/m = 1 dS/m = 1000 μS/cm).

Salinity is reported in a variety of units, such as parts per thousand (‰), parts per million (ppm), milligrams per litre (mg/L), osmotic potential (OP), and percentage total soluble salts in a 1:5 mix (%TSS 1:5). Various approximate factors exist for relating salinity measures but are based on assumptions about salt and soil type. As a rough guide, water with 15 000 mg/L TDS (total dissolved solids) has EC values around 2300 mS/m (TDS in mg/L $\approx$ 6.4*EC in mS/m).